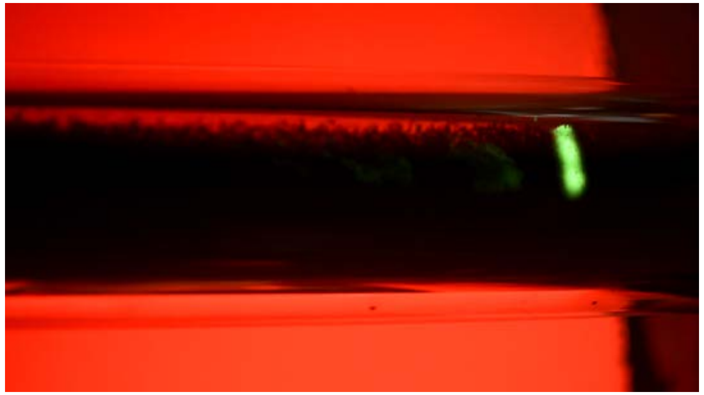
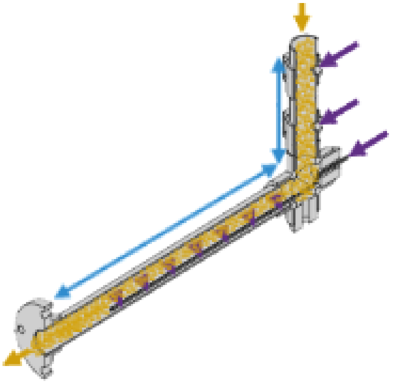
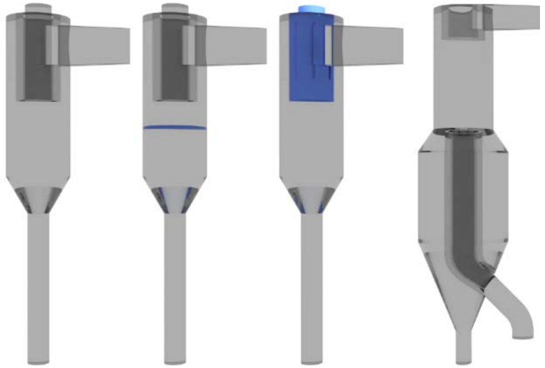
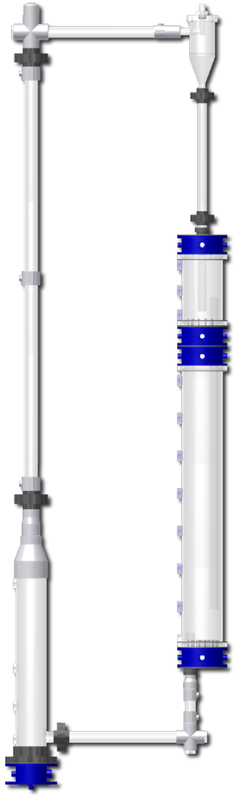
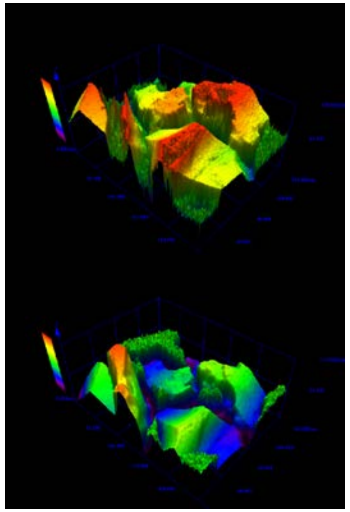









CHEMICAL LOOPING COMBUSTION RESEARCH AT NETL

Doug Straub
Mechanical Engineer, April 14, 2016

PRESENTATION OUTLINE

- **Overview status of CLC Technology**
  - Where Are We?
  - What Is Our End Goal?
- **FY16 NETL Chemical Looping Combustion Research Areas**
  - Scope and WBS
  - Task by task summary and overview
- **NETL's Chemical Looping Combustion Test Facility and Operating Experiences**
  - Nominal 50 kW_{th} CLC system
- **Summary And Future Work**

CLC Technology – Where Are We?

- **Preliminary techno-economic analyses (TEAs) have been completed**
  - Circulating reactor (Fe_2O_3 and $CaSO_4$) - DOE/NETL – 2014/1643
- **TEA Conclusions**
  - Significant amount of uncertainty 🡐 very little proven reliable operating data
  - Operability and reliability are major challenges for technology feasibility
  - Oxygen carrier makeup cost is a key factor for circulating reactor systems
- **Technology gaps identified by developers**
- **Multiple CLC test facilities do (or will) exist**

Exhibit ES-3 Cost of electricity breakdown comparison

Cost	Fe_2O_3 ($/MWh)	$CaSO_4$ ($/MWh)	Conventional PC BBR Case 12
Capital	49.6	53.4	73.1
Fixed	11.3	12.2	15.7
Variable	25.7	8.4	13.2
Maintenance materials	3.2	3.5	4.7
Water	0.4	0.4	0.9
Oxygen carrier makeup *	18.7	1.1	N/A
Other chemicals & catalyst	1.9	1.7	6.4
Waste disposal	1.4	1.7	1.3
Fuel	28.4	30.8	35.3
Total	115.1	104.7	137.3

*Fe_2O_3 oxygen carrier makeup: 132 tons/day @ $2,000 per ton; Limestone carrier makeup: 439 tons/day @ $33.5 per ton

CLC – What is Our End Goal?

GOAL:

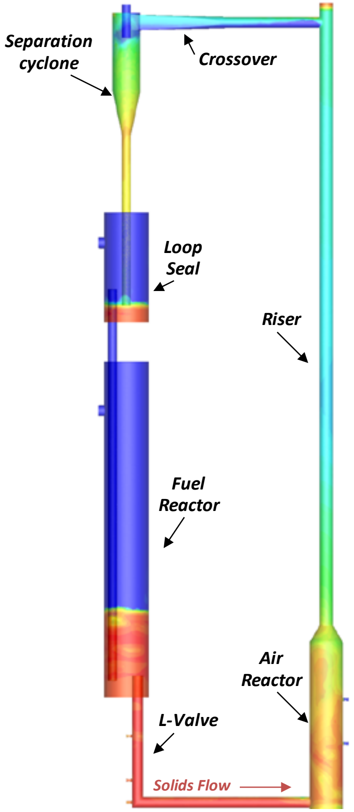
- **Determine if CLC is a feasible technology for FE and worthy of additional investment/development**
  - → Data and information for strategic decision making
- **If it is feasible, THEN**
  - – Help developers overcome technical issues
  - – Help technology be successful
  - – Ultimately commercialization
  - → jobs and growth

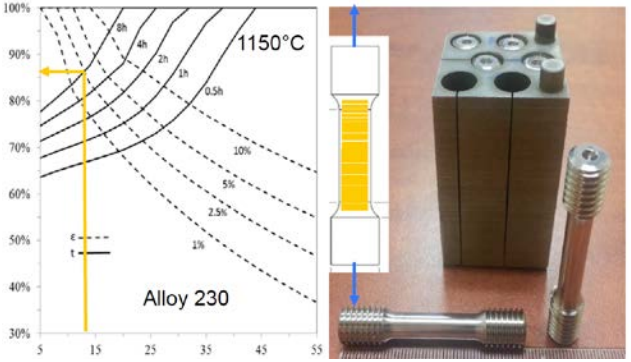
HOW DO WE GET THERE?

- **Focus on the “right” issues**
- **Build “world-class” expertise and capabilities**
- **Leverage both internal and external resources**

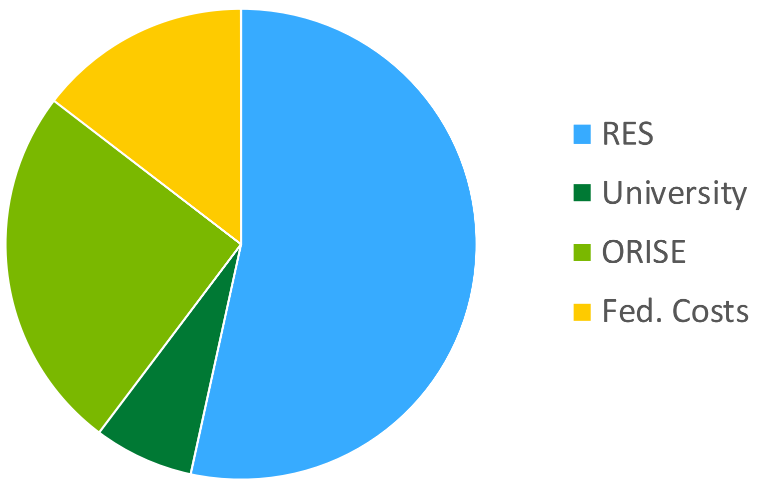
FY16 Advanced Combustion Scope

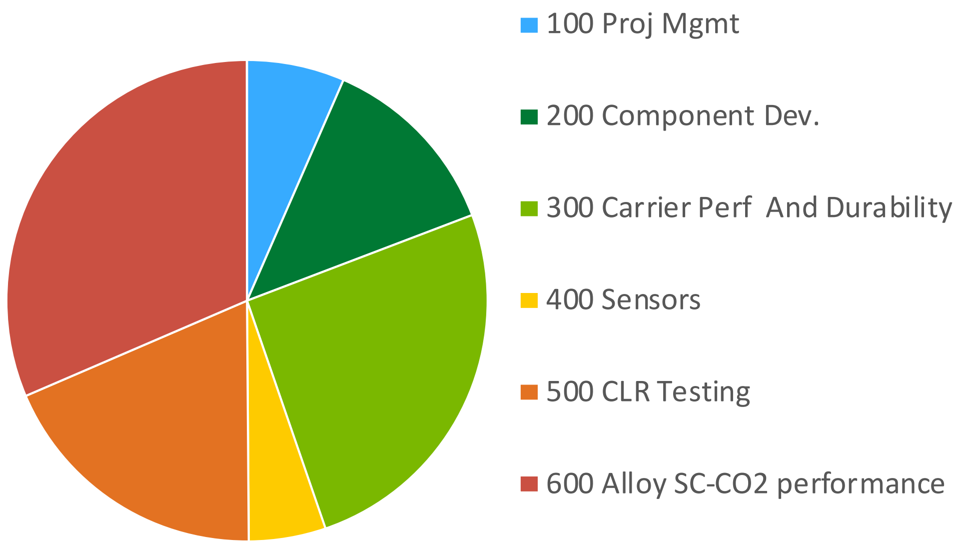
- **Address technology gaps that have been identified by key stakeholders**
  - Chemical looping combustion
  - Supercritical CO_2 heat exchangers
- **Key capabilities**
  - CFD tools for technology scale-up
  - Sensors that enable more reliable system control
  - Oxygen carrier materials (better performance, more durable)
  - Materials for supercritical CO_2 cycles





ADV. COMBUSTION BREAKDOWN BY TASK/ENTITY – FY16

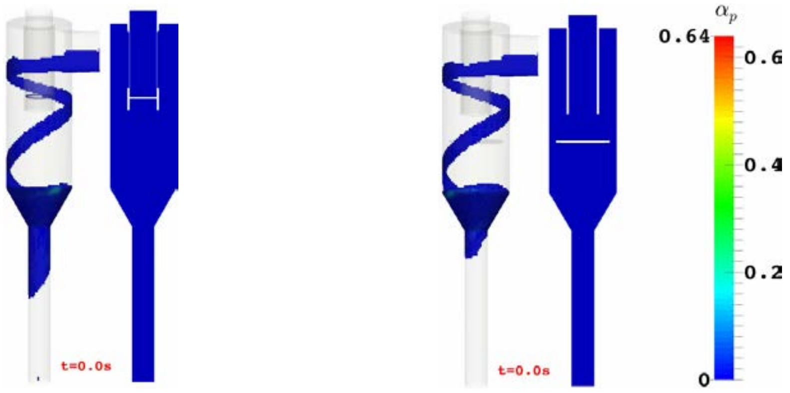




- **100 - Project Management**
- **200 - Component Development**
- **300 – Oxygen Carrier Performance and Durability**
- **400 – Sensors Development and Testing**
- **500 – Chemical Looping Test Bed Operations**
- **600 – Materials for supercritical CO_2 Cycles**

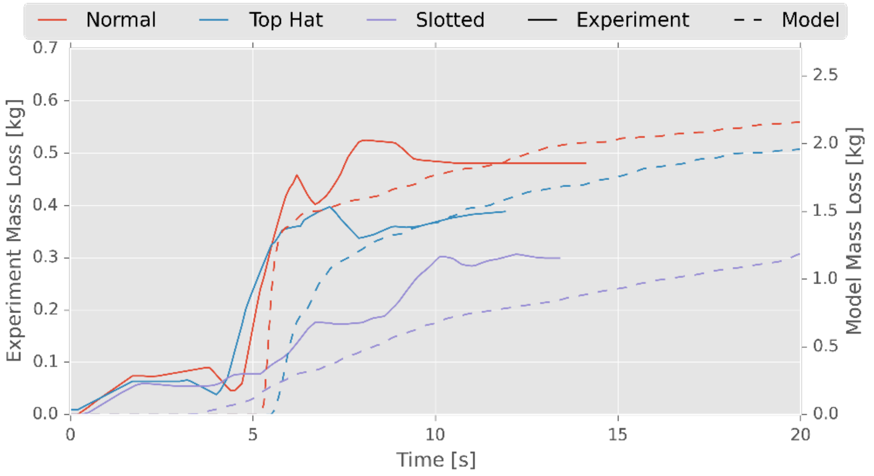
TASK 2 – COMPONENT DEVELOPMENT FOR CLC

- **Objectives**
  - Reduce carrier losses from conventional cyclone <u>during pressure upset</u> by an order of magnitude
  - Predict pressure drops for horizontal dense solids transport (small H/L aspect ratios) to within $\pm$0.1 psi with turn-around times of less than 48 hrs
  - Achieve char/carrier separation rates greater than 0.5 kg/m^2-sec for Group A/Group B and Group A/Group D mixtures
  - Preliminary scoping study on novel concepts

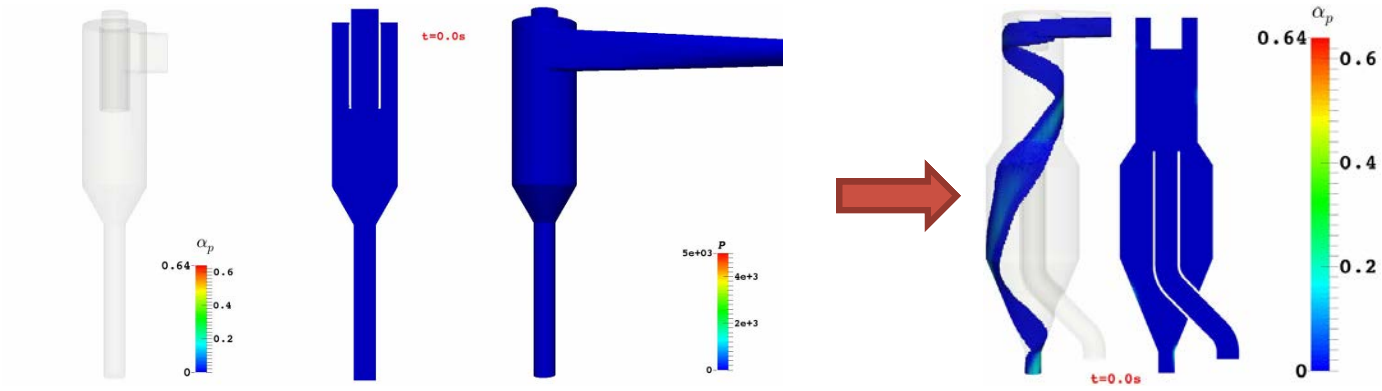


Slotted

Top-Hat



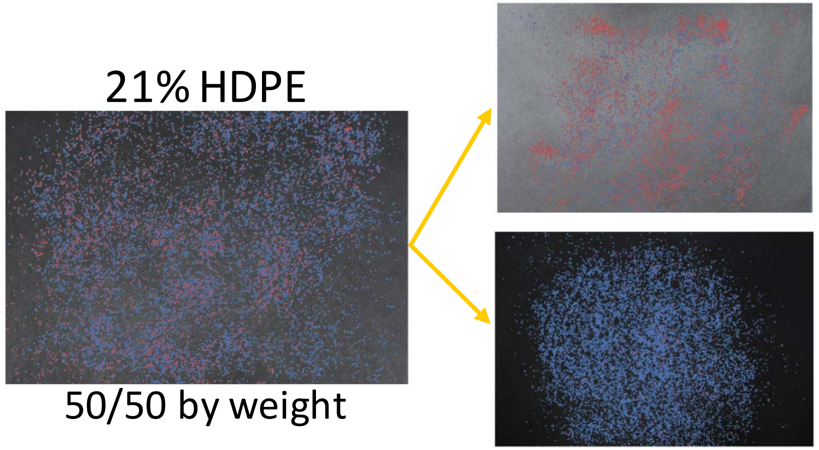
Design	Standard	Top-Hat	Slotted	Uniflow
Loss percentage [%]	95.06	98.31	82.24	8.62



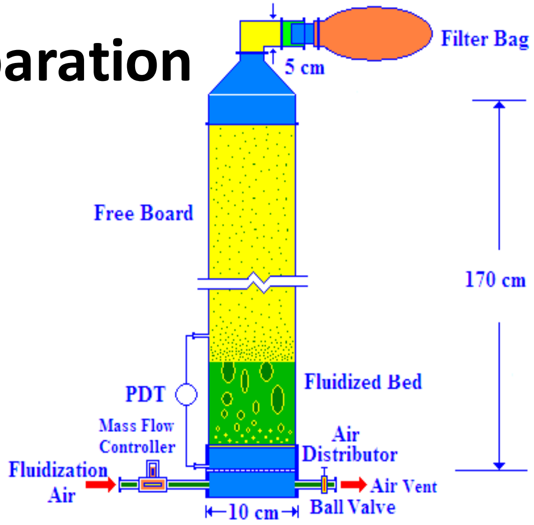
Uniflow

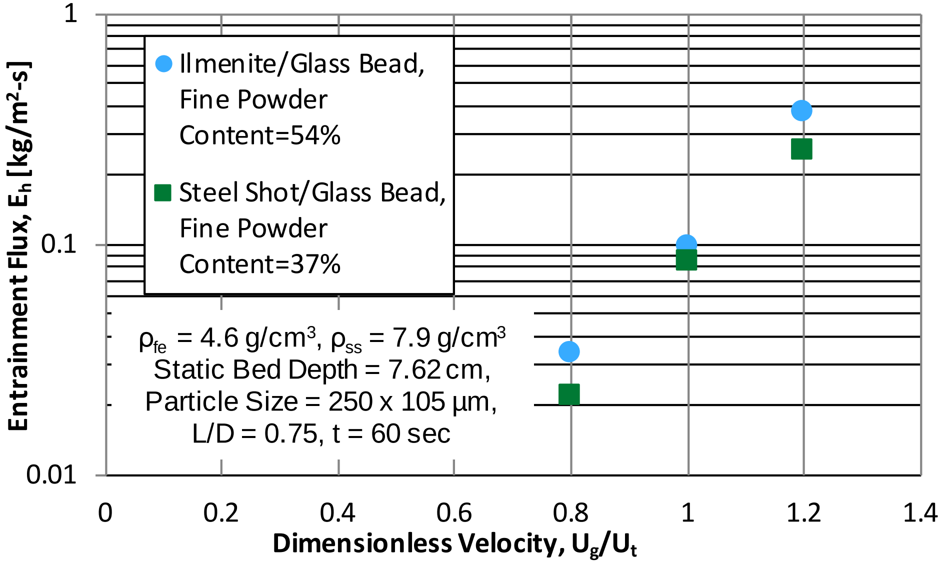
TASK 2 – COMPONENT DEVELOPMENT

- **Rotating fluidized bed**



- **Fluidized Bed Separation**





TASK 3 – OXYGEN CARRIER PERFORMANCE AND DURABILITY

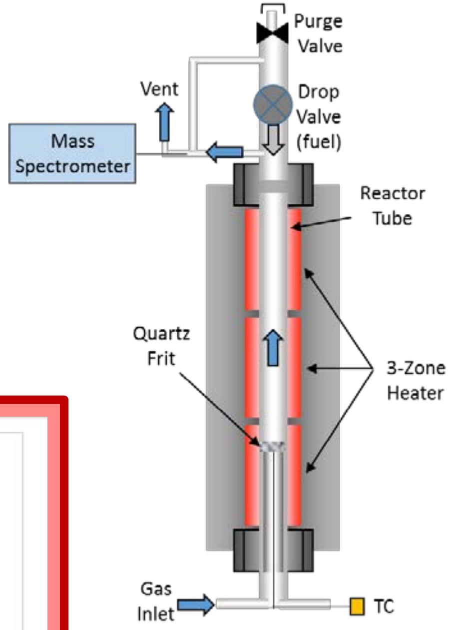
- **Carrier kinetics and tool development**
  - Guidance document for integrating oxygen carrier kinetic experiments with CFD reactor sub-models
- **Carrier improvement**
  - Develop more durable, lower cost Cu/Fe OC
  - Protocol for screening new carrier materials
  - Carrier manufacturing
- **Attrition studies in harsh environments**
  - Develop a simple attrition model
  - Shakedown high temperature jet cup
- **In-situ microstructural degradation**
  - Laser confocal microscope with hot stage
  - Monitor effects of temp, gas composition, and time independently

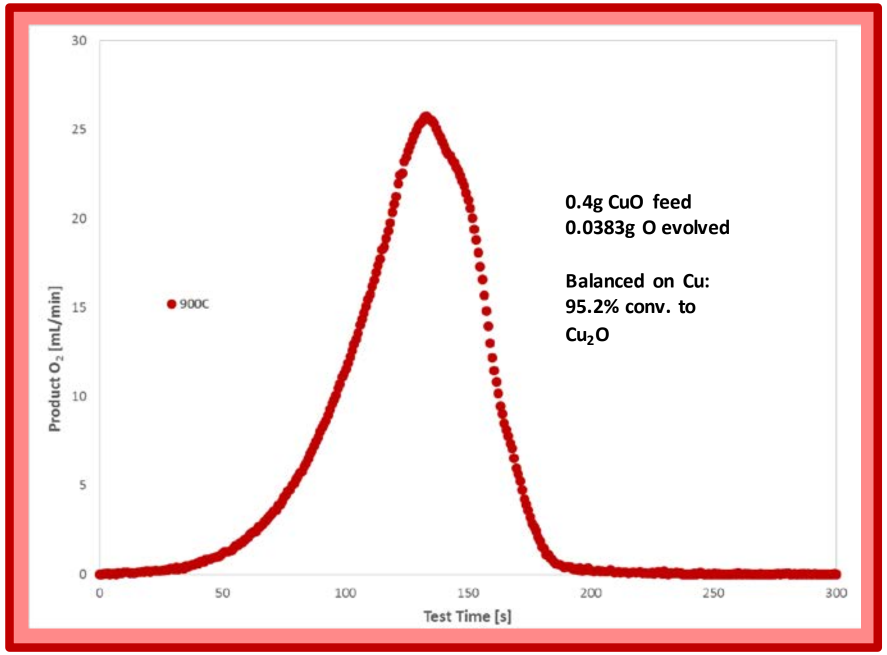
CLOU Oxygen Carrier (CuO)

$2CuO \rightarrow Cu_2O + ½ O_2$

Gas: Argon 1 slpm

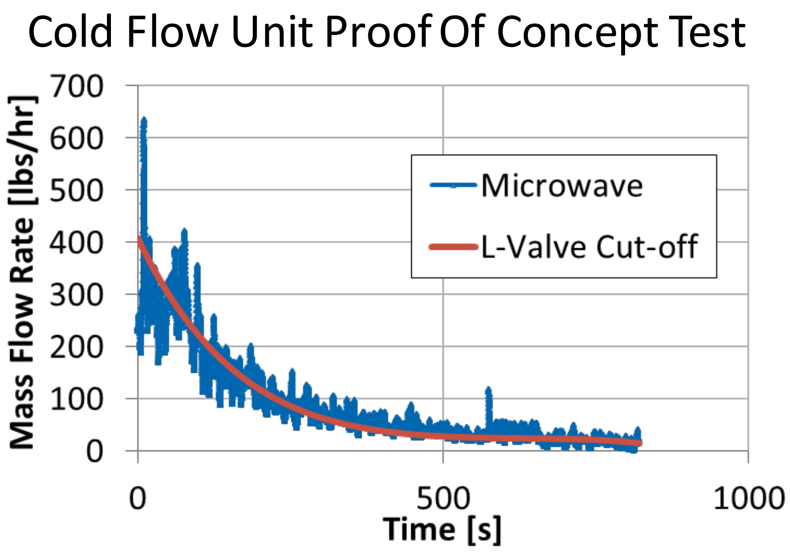
750°C – 900°C

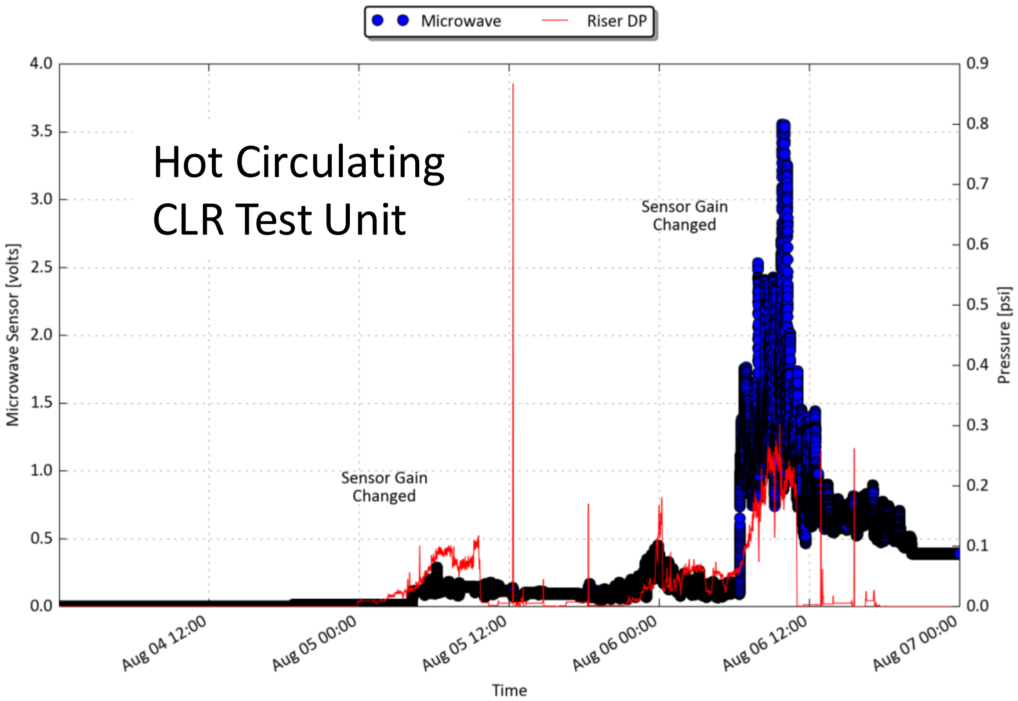


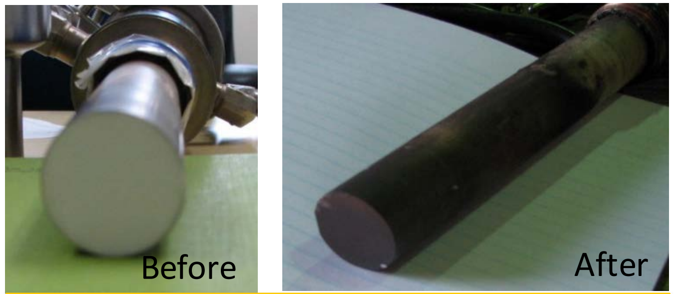


TASK 4 – SENSORS DEVELOPMENT AND DEMONSTRATION IN CLC SYSTEMS

- **Solids circulation**
  - NETL-CMU Microwave Doppler Sensor
  - Tested in NETL's 50kW Chemical Looping Reactor
  - Performance evaluation ongoing

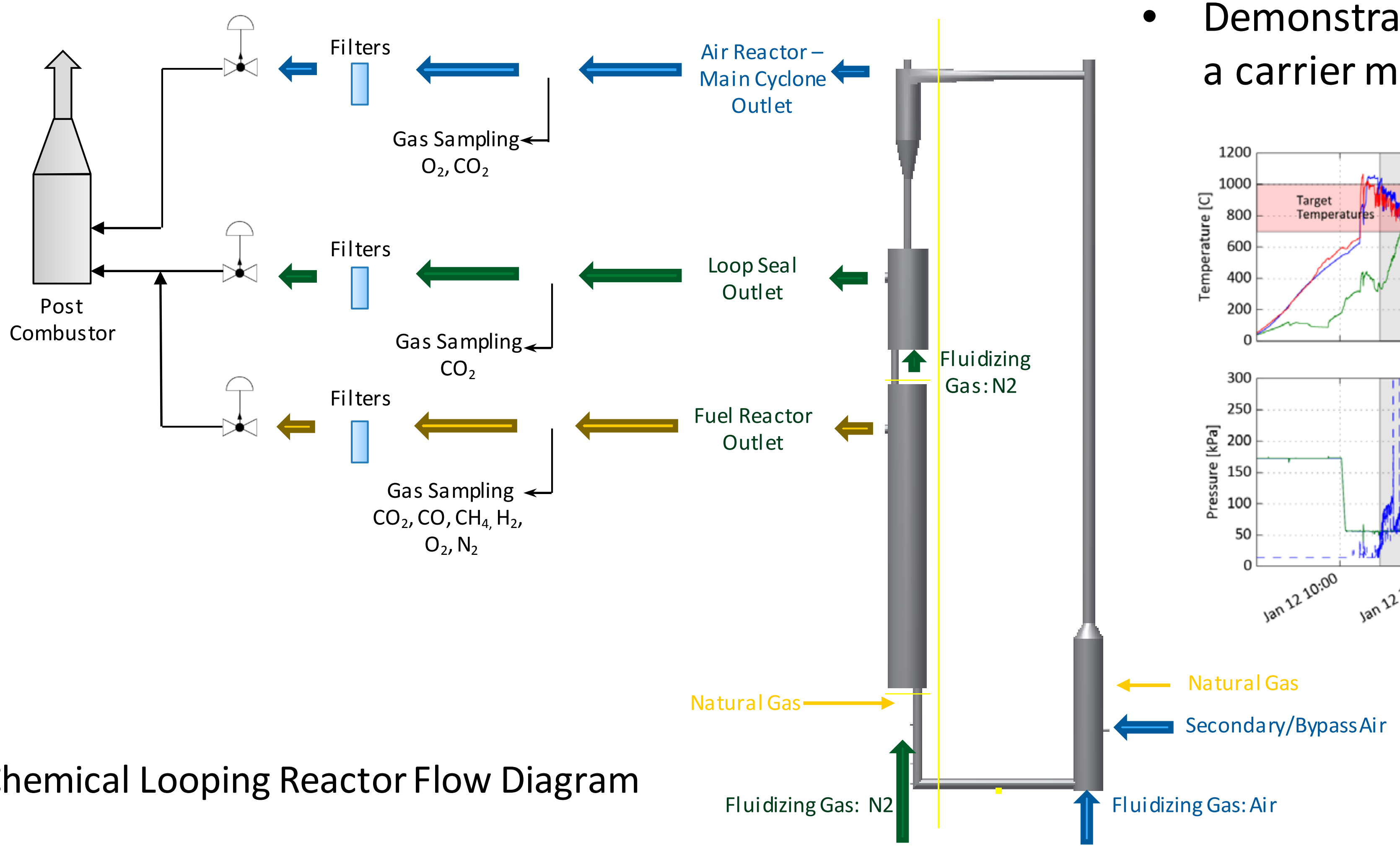






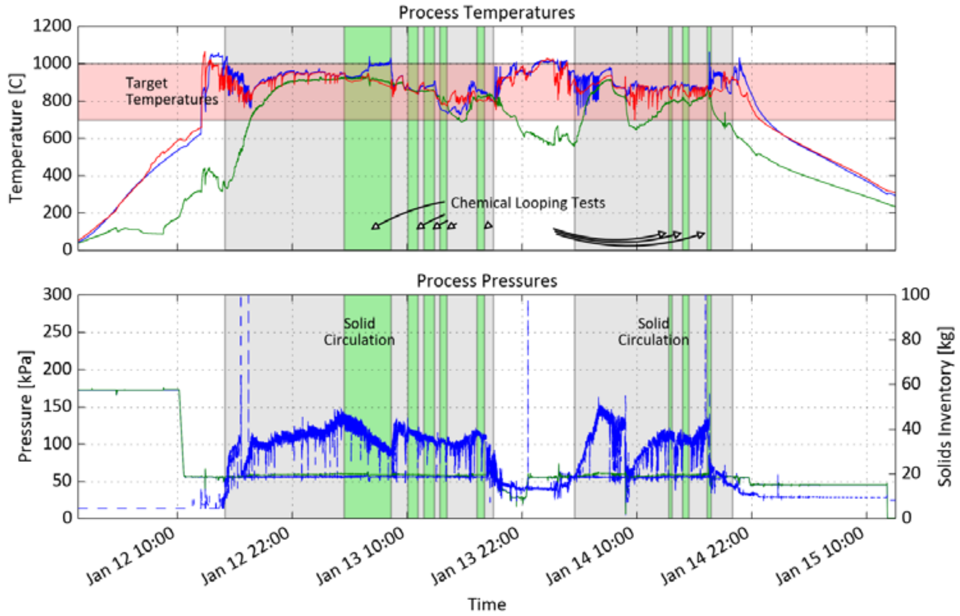
Conductive deposits on the alumina waveguide reduces signal

TASK 5 – CHEMICAL LOOPING REACTOR TESTING



Chemical Looping Reactor Flow Diagram

- Demonstrate continuous CL operation with a carrier makeup cost of $4/hr*MWt or less



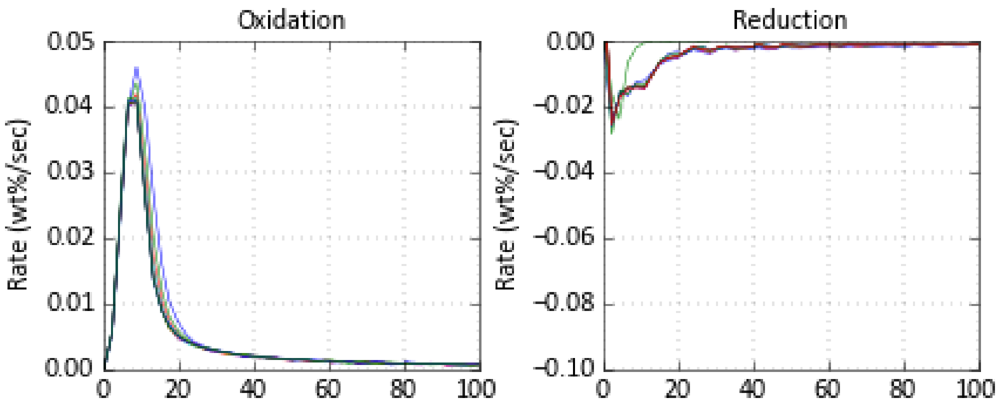
Operating Modes

- **Electric preheat**
  - Room temperature → Auto-ignition temperature
- **Natural gas augmented preheat**
  - 1200F to 2000F
  - Gas phase combustion in both reactors
- **Carrier addition**
  - Reduce gas flows
  - Add carrier in batches via lockhopper
- **Chemical looping combustion**
  - Transition from air to N2 as fluidizing gas in FR
  - Adjust natural gas flow for CLC

OXYGEN CARRIER – HEMATITE CONCENTRATE

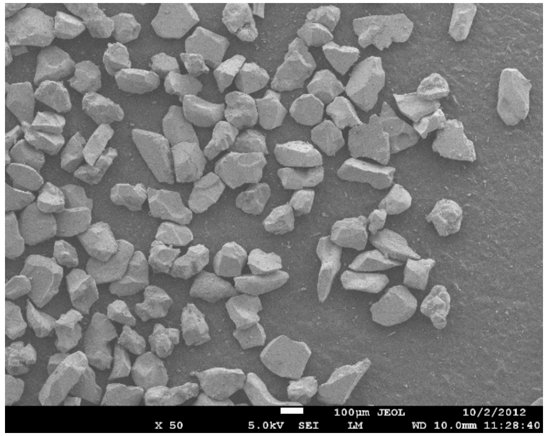
(WABUSH MINE, CANADA)

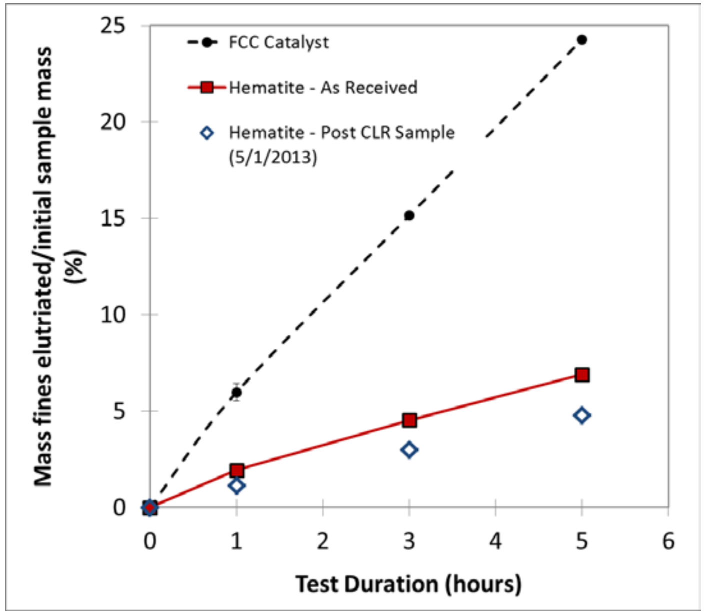
- **Relatively low cost**
- **High iron content**
- **Good attrition resistance**
- **Poor reactivity**

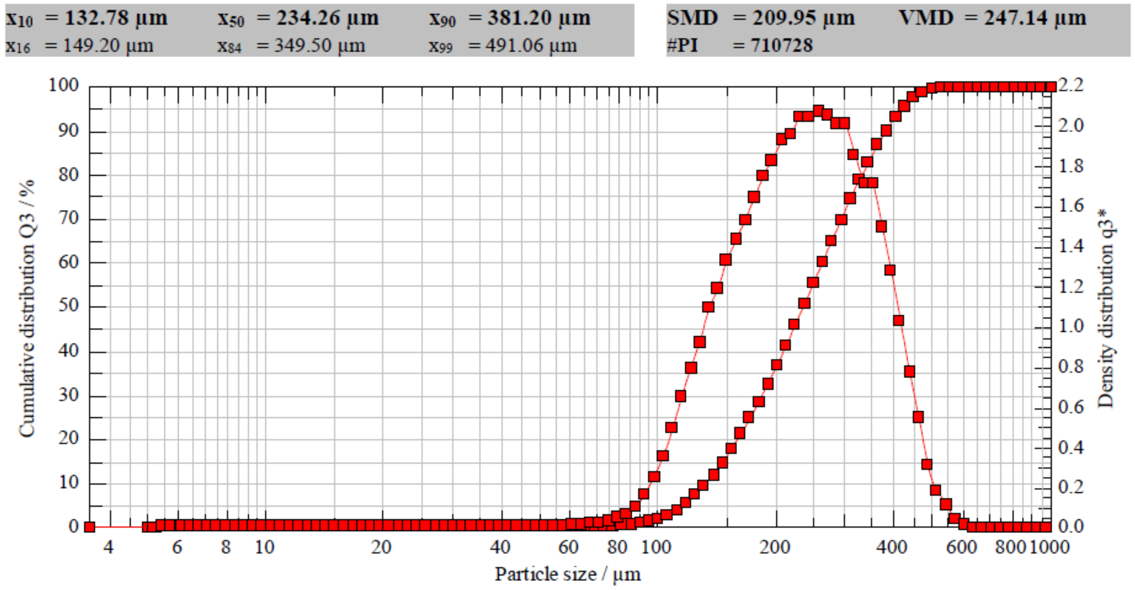


XRF Analysis

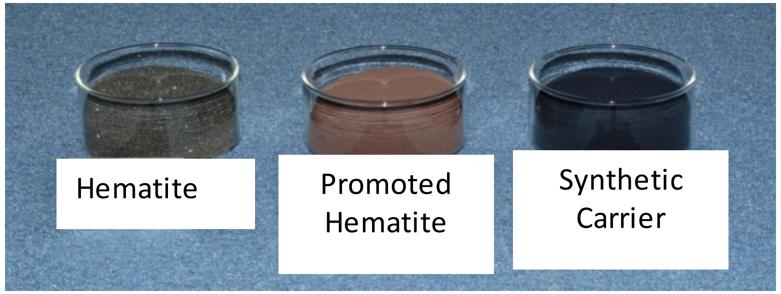
Fe_2O_3	81.89
SiO_2	12.10
MnO	5.63
Al_2O_3	0.24
K_2O	0.08
CaO	0.06



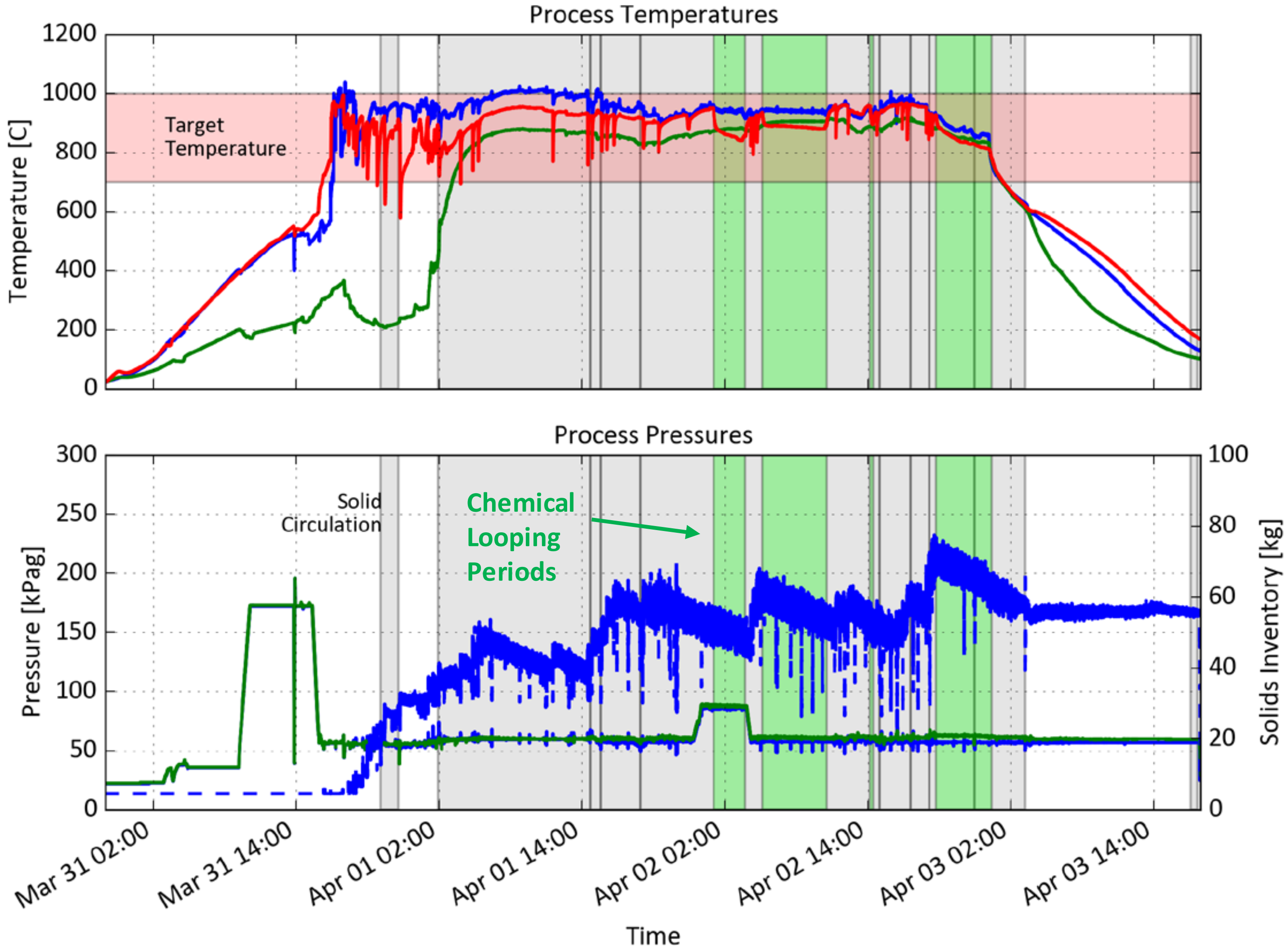




Process Data from NETL Unit – Promoted Hematite Carrier – 1st Test

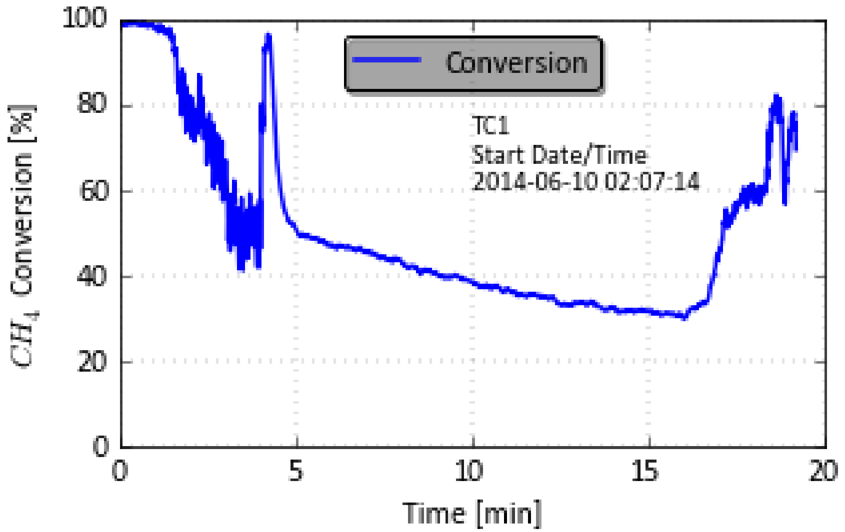


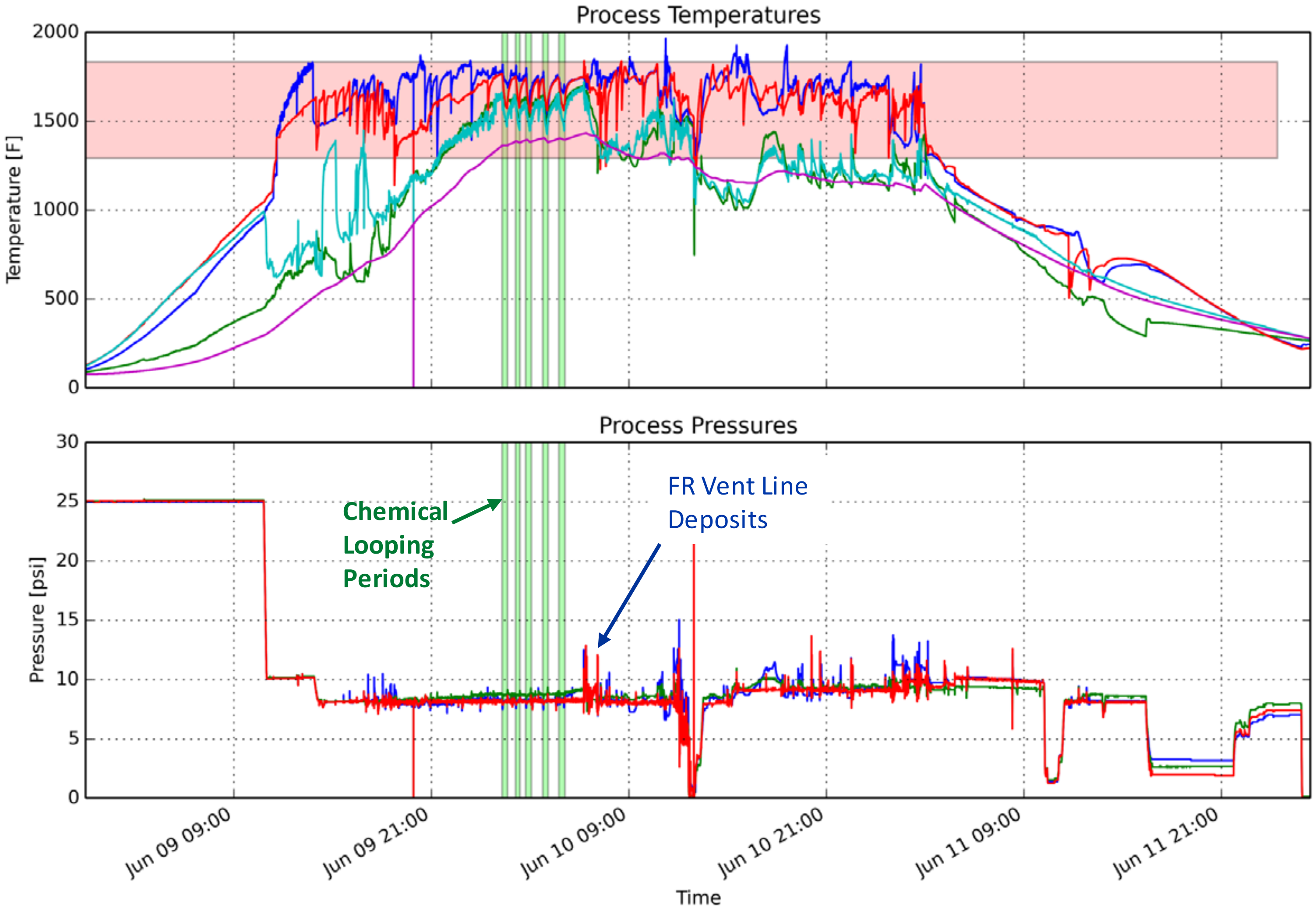
- **Over 12 hours of CL operation**
- **No significant process upsets**
- **Carbon balance was less than 90%**
  - Internal leakage through refractory in L-valve region
- **Fuel conversion typically less than 50%**



PROCESS DATA FROM NETL UNIT – PROMOTED HEMATITE CARRIER – 2ND TEST

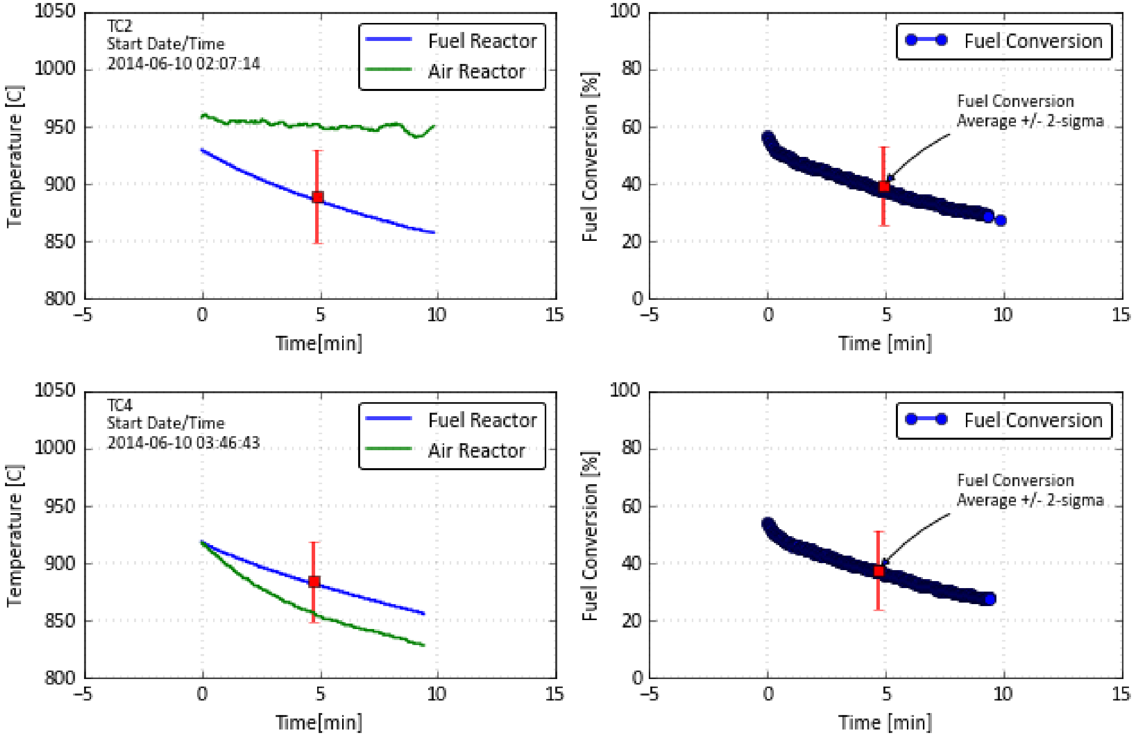
- **Carbon balance was significantly improved**
  - Greater than 90%
- **Fuel conversion still typically less than 50%**
- **Short duration test periods**
- **Operational issues encountered**





Source of Operational Issues

- **Cake-like deposits have been seen in tests with MgO promoted hematite carrier**
  - Deposits only in the FR vent lines (reducing environment)
  - Downstream/lower temperature components
- **Produced enough backpressure to affect pressure balance and control**



Summary Of NETL CLC Tests

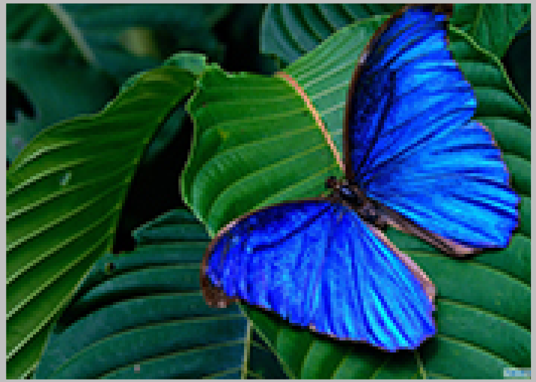
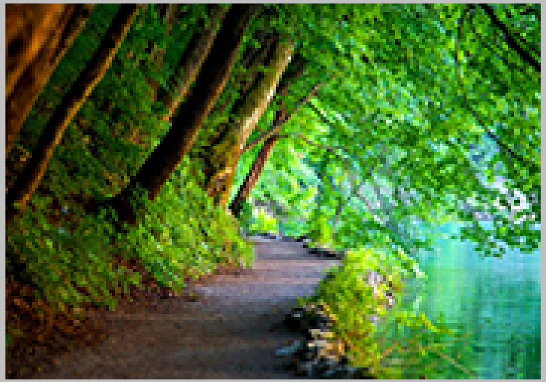
- **CLC technology has "potential" to achieve cost-effective reduction in GHG emissions from fossil-fueled combustion**
- **NETL's 50kW$_{th}$ CLC test facility**
  - Bubbling fluidized bed fuel reactor
  - Bubbling/turbulent fluidized bed air reactor
- **Tested several different oxygen carriers**
  - Hematite (Wabush Mine; Wabush, Newfoundland and Labrador, Canada)
  - MgO promoted hematite
- **Findings**
  - Mg promoted carrier materials produced coatings/cake in downstream lower temperature piping components
  - Operational pressure upsets have resulted in high rates of oxygen carrier loss
    - Pressure perturbations of 1-2 psi at rates of 1 psi/second have been recorded

Future Efforts

- **Establish baseline carrier loss/make-up requirements for this test rig**
  - Sensitivity studies have shown this to be a critical performance parameter
  - Need better solids mass closure
- **High temperature microwave doppler solids circulation sensor**
- **Collaborations on oxygen carrier testing are encouraged**
  - NETL attrition test unit would be used to screen materials
  - Quantity should be in the 100-150 kg range for one test

It’s All About a Clean, Affordable Energy Future



For More Information, Contact NETL

the ENERGY lab

Delivering Yesterday and Preparing for Tomorrow